02 May 2013, 4:00 pm - 6:00 pm

Earth Dam Failure by Erosion, A Case History

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Seventh International Conference on
Case Histories in Geotechnical Engineering
April 29 - May 4, 2013 CHICAGO
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EARTH DAM FAILURE BY EROSION, A CASE HISTORY

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ABSTRACT

In January 1998, the Archusa Creek Dam in southeast Mississippi failed by breaching through its emergency spillway. At the time of its failure, the dam had a concrete ogee weir for a principal spillway and a vegetated earth emergency spillway. Fortunately, the dam is a low hazard structure, as there is little development downstream, and consequences of failure were mostly limited to the loss of a state-owned, recreational water park. The dam failed as a result of a 5-year storm event, triggered by intense rainfall of nearly 4.25 in. in just a few hours. Runoff generated by the storm caused a rapid rise in lake level to elevation above the flood pool, resulting in flow over the emergency spillway. A breach then formed through the emergency spillway due to progressive erosion and head-cutting caused by excessive water flow velocity, a well-known failure mechanism. This paper examines how the failure happened, including the aspects leading up to the breach. Hydrologic, hydraulic, and geotechnical aspects of the failure are discussed, including the dam's design and subsequent modifications, its problems leading to failure, the engineering solution used to repair the dam, and how this solution solves the problems that led to failure in the first place.

INTRODUCTION

Archusa Creek Dam was built in 1971. Figure 1 illustrates the location of the dam near Quitman, Mississippi. A state agency owns the lake and dam; it is used exclusively for recreation (operation of a water park). The lake is shallow, with typical depth of about 1.2 m (4 ft), and generally ranging from 1.2 to 2.4 m (4 to 8 ft).

The lake is about 172 ha (425 ac). The size of the lake's watershed is about 15,800 ha (39,000 ac), resulting in significant in-flow to the lake during storm events. There is little storage volume available in the lake compared to in-flow; consequently, the dam must pass nearly all in-flow.

The lake is in the flood-plain of the Chickasawhay River. A high river stage produces tail-water below the dam that often exceeds the lake elevation.

Dam Details

The dam is built of compacted earth fill with a maximum height of 7.6 m (25 ft) and a length of about 1370 m (4,500 ft). The dam is homogenous, with no internal seepage control and no foundation cut-off. Fill material for the dam is generally fine silty sand as this soil was locally available for construction.

In the 1980s, the principal spillway was fitted with an inflatable gate; this configuration was modified in 1994 due to ongoing problems with maintenance and vandalism. In 1994, the spillway was modified with an ogee crest and series of sluice gates through the ogee. The crest and the gate inlets were all fitted with fish-retaining screens. Figure 2 illustrates these spillway modifications. Notably, the fish-retaining screens clogged with debris during the failure storm and contributed to breaching by restricting spillway capacity.

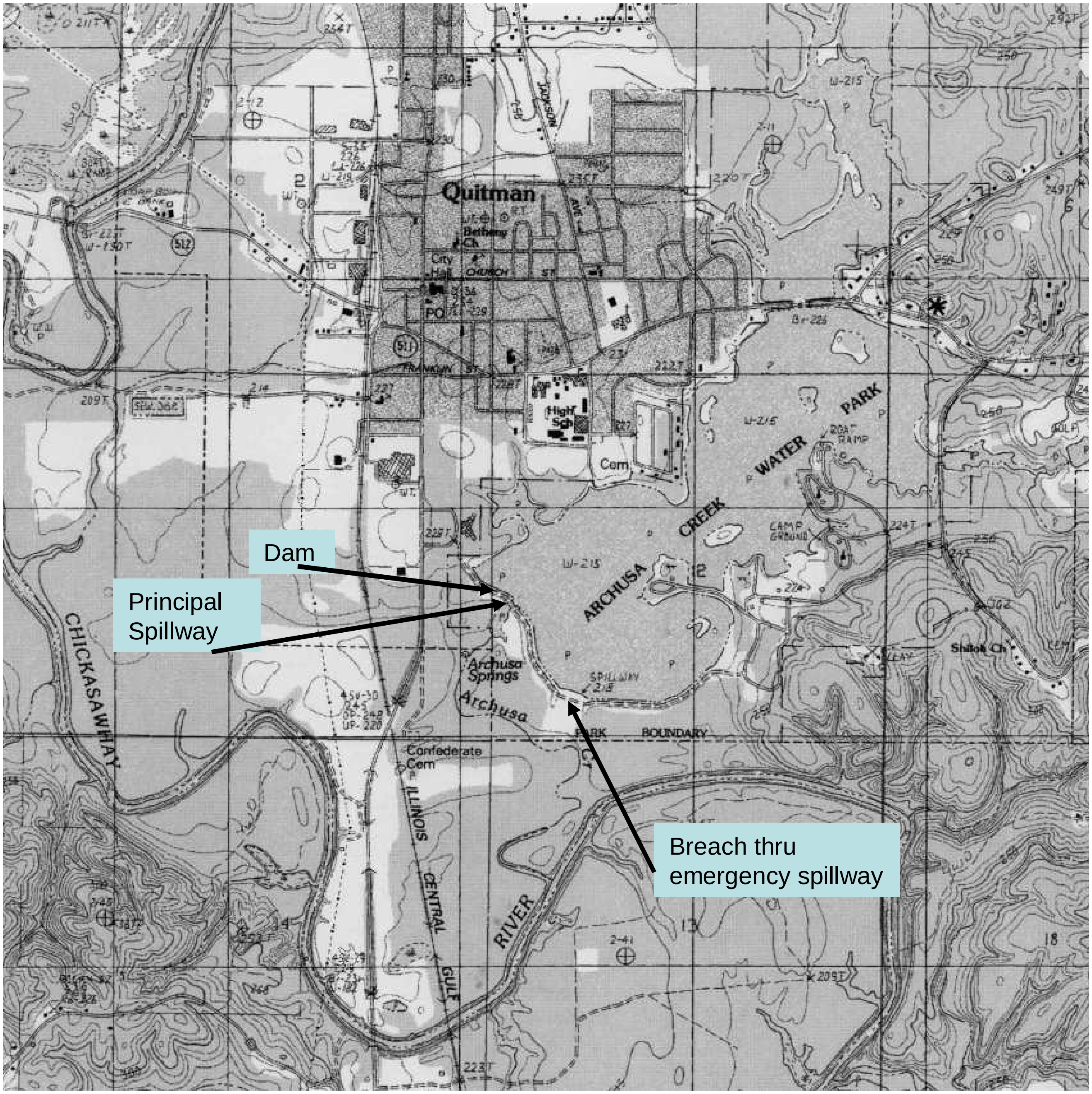

Fig. 1. Location map (source map USGS Quitman, Miss. Quadrangle, 1983).

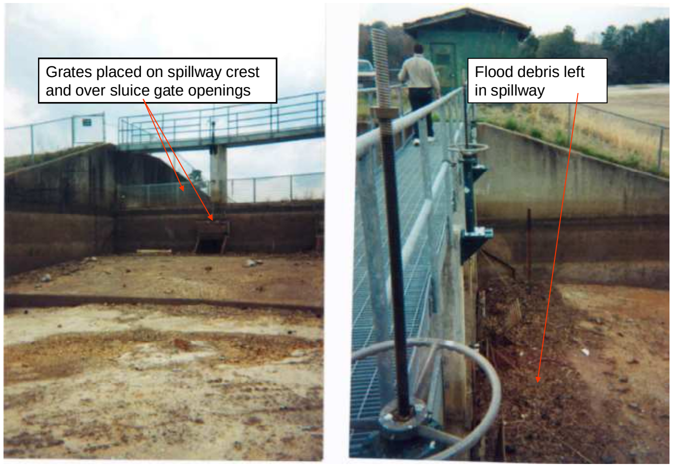

Fig. 2. Photo showing spillway modifications.

For passing in-flow exceeding the principal spillway capacity, the dam was designed with an uncontrolled emergency spillway, with a vegetated earth surface/lining. During the 1994 modification, the emergency spillway was widened from 120 m (400 ft) to 300 m (1,000 ft). This modification was effected by excavating the embankment down to spillway elevation over this portion of the dam. It was again modified shortly before the 1998 failure with the excavation of a drainage ditch within the spillway to facilitate rapid drainage of flood water from lake-side residential yards. Residents of several lake-side houses built within the flood pool had complained of water in their yards after storms that raised the lake to or near its flood-pool. The ditch excavation in the emergency spillway was undertaken to appease these complaints. This later modification contributed to the dam breach by initiating erosion in the emergency spillway.

Figures 1 and 3 illustrate the position of the emergency spillway on the dam. It is located near the middle of the dam at the maximum section as opposed to one of the abutments. Consequently, the soils below the emergency spillway were primarily fill, not native in-situ soil. The soil forming the emergency spillway was fine silty sand placed as fill. When the emergency spillway was widened, the excavation was extended into the sand fill placed to build the dam.

DETAILS OF DAM BREACH FAILURE

The breach was formed by the erosion of soil within the vegetated earth emergency spillway due to the high discharge velocity, which the spillway surface could not sustain. Figures 3 and 4 illustrate the position of the breach within the dam. The storm causing the failure was an event corresponding to a 5-year return period. Rainfall from this storm was nearly 16.5 cm (6.5 in.) in a 3-day period. However, the dam's failure was preceded by intense rainfall of 10.8 cm (4.25 in.) over a period of only a few hours. Figure 5 illustrates the grass lining on the emergency spillway, and shows the fine sand soil within the spillway. Figure 6 illustrates the lake's shallow depth (note the person standing to the right of the spillway, indicating relative scale).

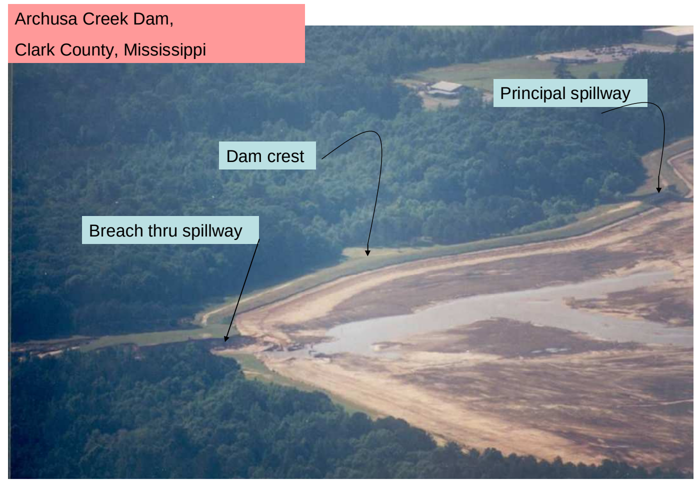

Fig. 3. Breach through emergency spillway.

Fig. 4. Close-up view of breach.

Fig. 5. Photo showing grass surface on spillway.

Fig. 6. Photo illustrating principal spillway and typical depth of lake.

Emergency Spillway Operation

Analysis shows that the emergency spillway would activate with a storm corresponding to a 2-year return period. Consequently, the emergency spillway was subjected to frequent flow. Hydraulic analysis indicates that flow in the emergency spillway in the 1998 failure storm was 200 m^3/s (7,000 cu ft/s), with a velocity exceeding 1.5 m/s (5 ft/s).

Erosion Mechanism

NRCS and USACE design references establish a range of velocity that a vegetated earth spillway can sustain. The Federal Energy Regulatory Commission (FERC) (2003) tabulates sustainable velocity listed in applicable NRCS and USACE design guide documents, as excerpted below, in Fig. 7. The NRCS document establishes a typical sustainable velocity in the range of 0.6 to 1.5 m/s (2 to 5 ft/s), depending on the base soil and the grass type. Maximum sustainable velocity (atypical) is about 2.4 m/s (8 ft/s) for a non-erodible soil and specific Bermuda species of grass.

Table III-3
Maximum Channel Velocities
(US Army Corps of Engineers, EM 1110-2-1601, 1991)

Channel Material	Mean Channel Velocity (ft/sec)
Fine Sand	2.0
Coarse Sand	4.0
Fine Gravel	6.0
Earth - Sandy Silt	2.0
Grass-lined Earth (slopes less than 5%)	
Bermuda Grass on Sandy Silt	6.0
Kentucky Blue Grass on Sandy Silt	5.0

The US Natural Resource Conservation Service (NRCS) (formerly the US Soil Conservation Service) provides maximum permissible velocities for channels lined with grass. The NRCS maximum permissible velocities for the relevant slope range are summarized on Table III-4 below.

Table III-4
Maximum Permissible Velocities for Grass Lined Channels
(US Natural Resource Conservation Service, Source: SCS 1985, Table 7-1)

Type of Cover	Slope Range (percent)	Permissible Velocity (ft/sec)	
		Erosion-resistant soils	Easily eroded soils
Bermuda Grass	0-5	8	6
Buffalo grass, Kentucky bluegrass	0-5	7	5
Sod-forming grass mixtures	0-5	5	4
Other grasses	0-5	3.5	2.5
Remarks: The values apply to average, uniform stands of each type of cover. Use velocities exceeding 5 ft/sec only where good covers and proper maintenance can be obtained.			

Fig. 7. Range of sustainable velocity on vegetated earth surface (FERC 2003).

The type of fine silty sand soil used as fill in the emergency spillway has a low resistance to erosion. According to the criteria in Fig. 7, maximum sustainable velocity on the Archusa Creek Dam's emergency spillway is 0.8 m/s (2.5 ft/s). Based on the calculated velocity during the 1998 failure storm near 1.5 m/s (5 ft/s), erosion through the spillway material would have been expected. The calculated velocity is based on the broad, flat spillway; the ditch excavated into the emergency spillway would have resulted in velocity exceeding 1.5 m/s (5 ft/s).

The specific erosion mechanism is illustrated and explained by Seed et al. (2006). This group extensively studied the soil erosion process in levee over-topping after the Hurricane Katrina disaster in New Orleans. The work by Seed et al. is not specifically applicable to vegetated earth spillways, but the erosion principle for soils is the same in the levee study and in the case of the dam spillway. Results of the New Orleans levee study match the specific events of the dam spillway: the erosion of a fine sand soil. The levee study parameters for velocity and critical shear stress apply to a bare soil without vegetation. For the dam spillway, once the vegetation was lost during the breach event, the resulting bare soil was then similar to the study condition.

Figure 8 illustrates that the fine silty sand soil within the dam's emergency spillway is generally the most easily eroded soil category and that erosion will result in this soil at a shear stress of about 0.1 N/m^2, the minimum for all soil types.

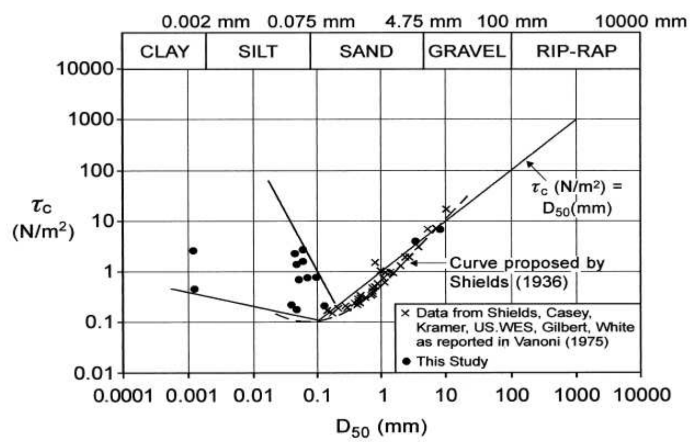

Fig. 8. Quantified measure of erodibility—critical shear stress versus mean soil grain size (Seed et al. 2006).

Figure 9 shows that for shear stress above the threshold value for fine sand, 0.1 N/m^2, a significant scour rate results. For the water velocity imparted to the spillway during the failure storm, exceeding 1.0 m/s, Fig. 8 indicates that the fine sand in the spillway would erode at a rate exceeding 1,000 mm/hr. These values apply to a bare soil not protected by vegetation. Accordingly, the values do not establish specific parameters

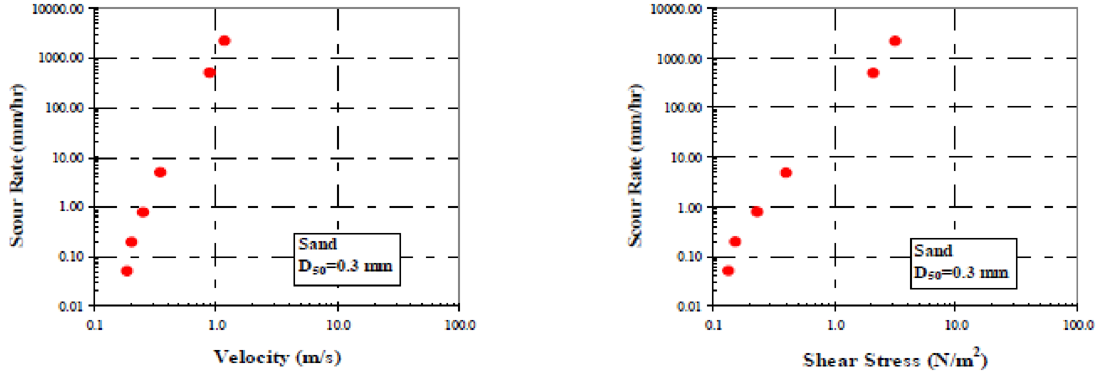

Fig. 9. Erodibility function for a sand (Seed et. al. 2006).

for velocity and erosion rates applicable to the dam spillway. However, Fig. 8 does provide aquantifiable indication that erosion would take place within the dam spillway during the breach storm event.

With the expected scour rate over 1,000 mm/hr and velocity imparted to the spillway exceeding 1 m/s, Fig. 10 illustrates that the spillway would have been highly erodible and prone to failure by overtopping. The levee study results depicted in Figs. 8 through 10, combined with the sustainable velocity range portrayed in Fig. 7, explain why erosion resulted in the spillway during the breach storm event.

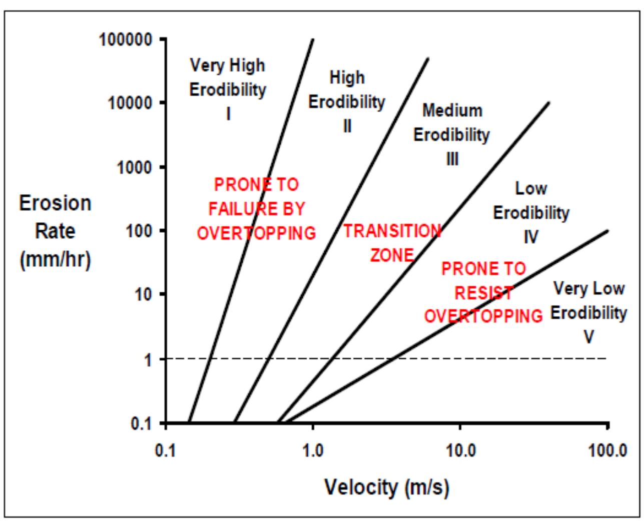

Fig. 10. Proposed guidelines for levee overtopping (Seed et al. 2006)

NRCS (1997) defines the specific process of erosion in earth dam spillways using a three-phase process:

1. The failure of the vegetal cover protection (if any) and the development of concentrated flow.
2. The downward and downstream erosion associated with the concentrated flow that leads to formation of a vertical or near-vertical head-cut in the vicinity of initial failure.
3. The upstream advance and deepening of the head-cut resulting from flow over the vertical or near-vertical face.

Figure 11 illustrates the three-phase mechanism described above for over-topping failure in earth dams. Failure is initiated by erosion of the soil particles due to excess velocity. A near-vertical face is formed, which travels progressively toward the reservoir during the erosion process (head-cutting). Finally the head-cutting process effects complete breach of the dam.

Overtopping is essentially the same erosion process that takes place in a vegetated earth spillway. This is especially true for the Archusa Creek Dam, as addressed in the DISCUSSION section of this paper.

DISCUSSION

Consequences of Failure

The dam was not a high hazard structure; consequences of failure had little effect on downstream property or infrastructure. As Fig. 2 illustrates, the Chickasawhay River is just downstream, close to the spillway discharge channel. Downstream development is sparse due to the river's floodplain. At the time of the dam breach, local media reported a "wall of water" released from the dam. In fact, during the storm event, river stage rose above the lake elevation. Shortly after the dam breach, rising tail-water flowed into the reservoir from the river. Obviously there was no wall of water produced by the breach.

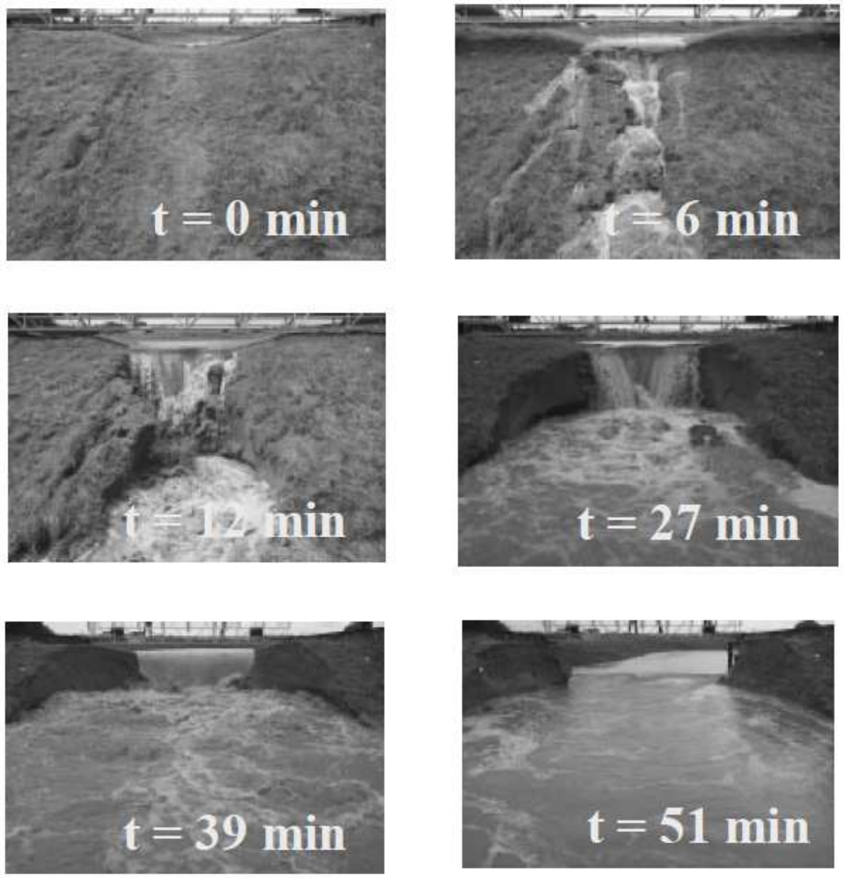

Fig. 11. Illustration of dam breach by overtopping- embankment breach test of a homogeneous non-plastic sandy soil conducted at the ARS Hydraulic Laboratory, Stillwater, OK (FEMA 2001).

The real consequences of failure were economic ones. The water park was a prominent part of the local economy; the small community was dependent on it, and local merchants suffered when it was closed. The cost of repair to the dam was the most significant consequence, an estimated cost of $1.3 million.

Earth Spillway Design

Established design methods call for earth spillways to be located at abutments and founded in cut to prevent the erosion of fill soil. The NRCS has extensive guidance for location, alignment, and grade for an emergency spillway (summarized below) so that erosion will not cause a breach failure. Figure 12 illustrates design guidance for these criteria.

- Location—The most important element of location is to place the spillway where erosion and breach does not result in dam failure. As discussed above, this criterion is met by locating the spillway at an abutment, cut into native soil (alternatively the spillway can be cut through a saddle in terrain on the lake perimeter). Preferred location for the spillway is where it can discharge downstream without flow onto the toe of the dam. For sites where this alignment is impractical, training dikes can be used to keep flow off of the dam toe, but this configuration is not preferable.

- Alignment and grade—The spillway control section is designed to reduce velocity over the spillway to a sustainable level. Alignment and slope on the spillway are set so that velocity stays within the sustainable range for the length of the spillway.

The earthen emergency spillway design for the Archusa Creek Dam did not conform to these criteria. The spillway was located in the middle of the dam, with its bottom in fill where it should have been at an abutment in cut. The spillway did not have a control section sufficient to lower velocity to a sustainable level. Further, the drainage ditch excavated into the spillway concentrated flow and increased velocity, initiating erosion during the failure storm.

With the emergency spillway out of conformance with these guidelines, erosion was a threat to dam safety. The choice of grass for the emergency spillway lining was inappropriate. Some armored lining, e.g., rip-rap, would be required for the emergency spillway geometry in order to prevent erosion that could result in dam breach.

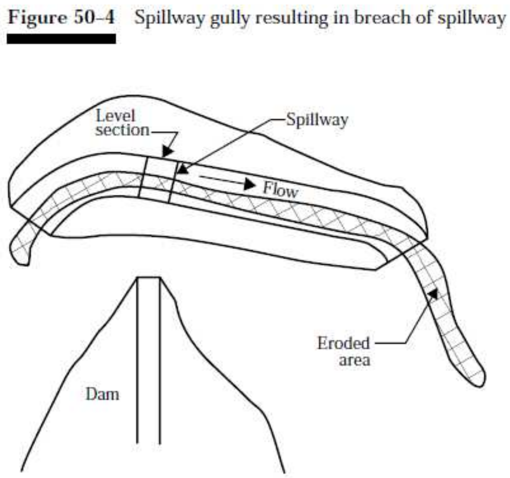

Fig. 12. Diagram illustrating proper emergency spillway layout (From NRCS (1997)).

Hydraulic Design

NRCS design guides and most state regulations require that reservoir storage and principal spillway capacity allow for flow over an emergency spillway at a storm return period of 100 years. The 1998 configuration of the Archusa Creek Dam emergency spillway resulted in flow on an almost 2-year frequency.

CONCLUSIONS AND PROMINENT LESSONS

For the 1998 dam configuration, the earth emergency spillway had an activation frequency of every 2 years, where this frequency by current design standards should have been closer to 100 years. Consequently, the emergency spillway was used frequently, not on an emergency basis. For this frequency of use, the spillway should have been an armored auxiliary one.

The dam breach was actually an over-topping failure. Because the earth emergency spillway was located in the interior of the dam (versus at an abutment), and built on fill (versus in cut), water flowing over this surface was essentially the same as flowing over the dam.

This case shows the merit of the NRCS design guidance for earth emergency spillways. The features of the Archusa Creek Dam's emergency spillway that did not conform to the NRCS design guide were the major factors leading to failure:

- Location on the dam— The spillway was located near the center of the dam, in a position where erosion led to breach through the dam. It was not positioned at the abutment cut into native soil.

- Spillway surface—The surface was in fill versus cut into native soil. The use of erodible fill soil in the spillway established the speed limit for water flowing over it, roughly 0.8 m/s (2.5 ft/s). The 1998 storm produced flow with velocity much greater than this limit.

- Lack of control section—There was no means to control velocity at the spillway entrance. With no control section, the excavation of the ditch into the emergency spillway set up a flow velocity that would exceed the speed limit discussed above.

- Unsuitable lining—Grass over erodible soil would not sustain the discharge velocity and frequency.

Setting the Stage for Failure—A Speed Limit on the Emergency Spillway

Modifications to the dam set the stage for failure. The so-called widening of the emergency spillway was essentially lowering the top of the dam, thus reducing freeboard. Excavating into the dam at the position of the emergency spillway near the middle of the dam involved excavating embankment fill material. This operation essentially lowered the top of the dam. With reduced freeboard and a design that entailed the storm pool to reach the emergency spillway on a 2-year frequency, the stage was set for failure by over-topping.

The modification to the principal spillway added another element for potential failure. Changes in the principal spillway included the addition of an ogee weir with manual sluice gates. The gates and the weir crest were all fitted with fish-retaining grates, as illustrated in Fig. 2. As Fig. 2 illustrates, the grates collected significant debris during the storm event, consequently restricting flow capacity through and over the spillway. The reduced capacity from the clogged grates was probably never envisioned or accounted for in the dam modification. While the disadvantage of grates over the spillway openings is evident, there is little known benefit.

The final modification, excavation of a ditch into the emergency spillway, was the factor that put the failure mechanism into motion. After this modification, the only required ingredient was a storm of sufficient size to raise the lake above flood-pool and send water over the emergency spillway with sufficient velocity. The modifications to the dam had established a speed limit for water over the vegetated emergency spillway. Unfortunately, nature would not abide by this speed limit and supplied a flow of water exceeding it. Flow on the spillway exceeding the speed limit initiated the failure by starting the erosion process that steadily progressed to a breach.

Repair

Several alternatives were considered for repair of the dam and its return to service. Immediately after the dam failure, local government proposed $500,000 in funding to re-fill the breach and return the dam to service. However, it was pointed out that this investment would only put the dam back into the same deficient condition that it was in when it failed.

A concrete labyrinth weir spillway was selected as the main repair component; it was built within the gully made by the breach. This new concrete spillway, now used as an auxiliary spillway, has helped designers solve the problem of flow over an earthen emergency spillway at a 2-year frequency and should prevent such a disaster in the future.

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